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FISSION PRODUCT DECAY CHAINS: SCHEMATICS WITH  
BRANCHING FRACTIONS, HALF-LIVES, AND  
LITERATURE REFERENCES

by

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## ABSTRACT

Schematic diagrams of the decay chains for the fission products of uranium and plutonium are presented, with half-lives of the nuclides, branching fractions, and literature references. The updated data were obtained from a review of the literature through February 1967.

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## SUMMARY

### The Problem

Precise descriptions of the genetic relationships in fission-product decay chains, as well as half-life values for the radionuclides comprising the chains, are required for the calculation of the radiation properties of fission-product mixtures.

### Findings

Accurate knowledge of these properties is required in assessments of the consequences of reactor operations and accidents, nuclear weapon testing, and nuclear warfare. Updated individual radionuclide data were obtained by review of the literature through February 1967. The information is presented in schematic form, along with literature references.

## INTRODUCTION

The neutron fission of uranium or plutonium produces several hundred radionuclides, mostly beta-emitters, belonging to about 90 mass chains. Calculation of the radiation properties of fission-product mixtures as a function of time requires precise descriptions of the decay chains, including the parent-daughter relationships of the nuclides, the branching fractions where the chains are branched, and the half-lives of all the nuclides.\*

This kind of information has been generated and/or collected at this laboratory and utilized in computer calculations of fission-product abundances and activities for several years. An early version of the decay chains was published in Ref. A. Many of the half-lives in that version were estimated and some chain-branching fractions were arbitrarily assigned. Also, a sizable number of metastable states among the fission products were not known to exist at that time. The appearance of Katcoff's (Ref. B) and Stehn's (Ref. C) chain data led to considerable improvement. In 1964, a new version (Ref. D) of the fission-product decay chains, based largely on the decay schemes through 1963, in the Nuclear Data Sheets (NDS), see Ref. F, was prepared for use in this laboratory.

The collection of new data has continued and a large number of changes has accumulated since 1963. These were incorporated into the decay chains, of which the latest versions are presented here.

## SOURCES

The list of references is divided into (1) general references, which are cited by the letters A through F; and (2) numbered references, which were sources of specific items of information. The decay chains and the data as presented evolved via References A, B, C, and the NDS data sheets, except where indicated by parenthesized citations of the sources in the specific reference list.

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\*The independent yields of the nuclides are required as well, but these are not treated here. Predicted independent yields for several fission types can be found in Ref. 71.

The data collected since 1963 which have been incorporated into this presentation were accumulated by regular and systematic perusal of periodicals and reports in the nuclear science field. The pertinent information tends to appear in a handful of major journals, as a cursory examination of the list of references will confirm, and it is believed that most of these were considered. A crosscheck with the 1964 and 1966 Recent References of NDS has provided welcome reassurance that no very sizable body of publication was overlooked. Another crosscheck was provided by the reference list (through 1963) in Herrmann's excellent historical account of fission-product radiochemistry, Ref. E.

Since most of the NDS decay schemes for the fission-product mass chains (on which Ref. D was based) have not been revised since 1961 or earlier, the chain data presented here incorporate a large number of more recently published values. Many of the changes are minor, but some are important. The reports on which the changes are based have not been subjected to the critical study and evaluation which the Nuclear Data Group will eventually provide. The chain data as presented here should therefore be regarded as an interim summary, subject to further emendation and amplification.

The intention was to include in the chains all the products, including isomers with half-lives greater than 0.5 seconds, known to occur in the neutron fission of uranium and plutonium. Mass chains lower than mass 72 or higher than mass 161 were disregarded because of their insignificant contributions. Many of the short-lived nuclides at the beginnings of the chains have never been observed in fission products, but their presence is predicted by the models of charge distribution. Some of the shielded nuclides shown at the ends of the chains may not be produced in detectable amounts. However, very small yields of  $^{86}\text{Rb}$  and  $^{134}\text{Cs}$  have been reported<sup>70</sup> and it seems possible that similar shielded end-members in other chains will eventually be identified in fission products.

Some important gaps in the information remain. The lack of half-life values for short-lived early chain members is conspicuous. Almost all the chains begin with a few members whose half-lives are only roughly estimated at best. Estimated half-lives are marked with an asterisk and are mostly taken from Ref. A. Experience has shown that they may be in error by several orders of magnitude. Branching fractions are frequently unknown or are uncertain, particularly in the more complicated chains. Estimated branching fractions, also asterisked, are usually an arbitrary 50-50 splitting, but in a few cases have some basis in reports of fragmentary or incomplete studies. It is often unknown which of two states of a nuclide is the ground state. For calculational and schematic purposes, distinguishing symbolism is desirable, nevertheless. Therefore arbitrary assignments of "metastable" and "ground" states were made in cases of uncertainty.

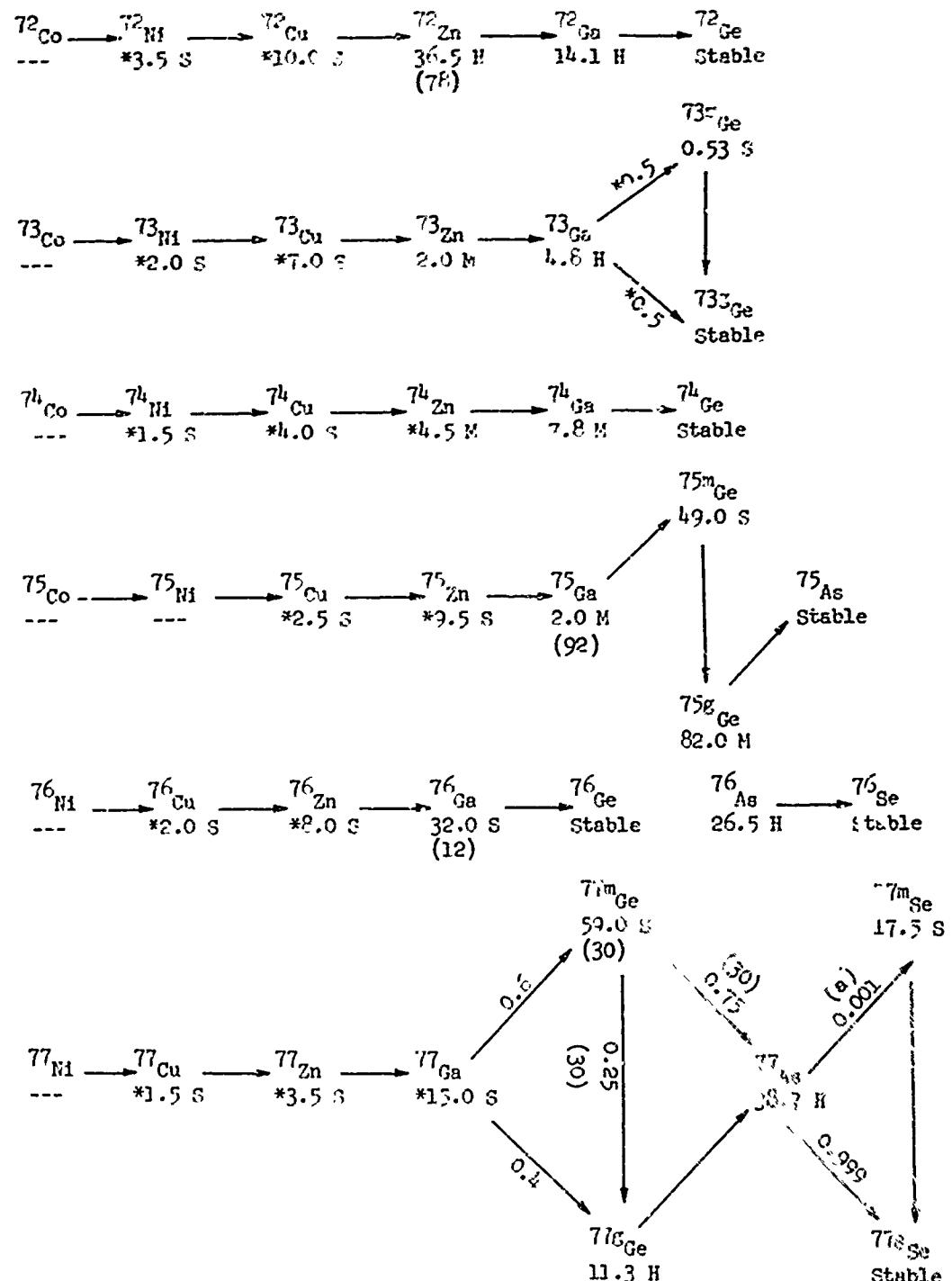
The relationship of several short-lived states to the fission process and to the chain-decay path (or paths) is unknown. On the other hand, most of the longer-lived chain members have been well characterized and their positions in the chains are fairly certainly known. However, some exceptions exist. It is not clear, for instance, whether the mass-98 chain decays mainly through a 51-minute or a 2-minute isomer; or, indeed, whether either of these half-lives is correct. Certain chain-decay features, once regarded as well-established, have required important modifications. For instance, until recently the mass-117 chain was believed to decay partly through a 3-hour  $^{117m}\text{Cd}$  and partly through a 50-minute  $^{117g}\text{Cd}$ . Now both isomers of  $^{117}\text{Cd}$  are known to have half-lives near 3 hours.<sup>20, 34, 44, 59, 60</sup> (The further decay pathways of the mass-117 chain through two In isomers and two Sn isomers remain uncertain.) Similarly, the reported 1-hour state of  $^{129}\text{Sn}$  recently was established as one of about 6 minutes.<sup>40</sup> It is quite possible that further important changes of this kind may occasionally be necessary.

#### NOTATION

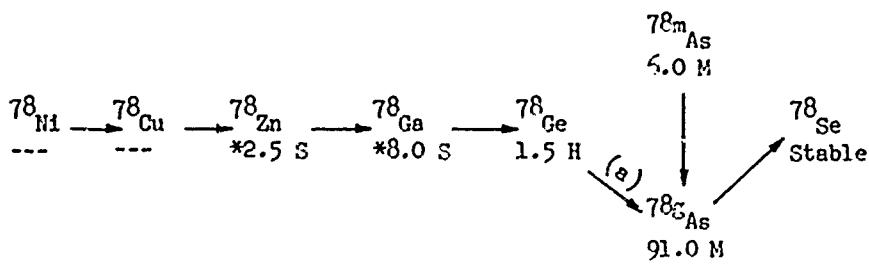
The decay chains are represented in the conventional symbolism with arrows indicating parent-daughter relationships. Branching fractions are written along the arrows where chain branching occurs. Half-lives are written below the nuclides, with abbreviations S for seconds, M for minutes, H for hours, D for days and Y for years. The numbers in parentheses which accompany some of the data refer to the sources in the List of References. Half-lives and branching fractions marked with an asterisk are estimates (see preceding section).

The arrows ordinarily indicate negatron decay but in a few cases ( $^{122g}\text{Sb}$ ,  $^{128}\text{I}$ ,  $^{152m}\text{Eu}$  and  $^{152g}\text{Eu}$ ), where the direction of the arrow is reversed, either positron emission or electron capture, or a combination of the two, occurs. Decay by neutron emission to the mass chain of next lower number is indicated by dotted lines for  $^{85}\text{As}$ ,  $^{87}\text{Ir}$ ,  $^{88}\text{Br}$ ,  $^{89}\text{Br}$ ,  $^{90}\text{Br}$ ,  $^{137}\text{I}$ ,  $^{138}\text{I}$  and  $^{139}\text{I}$ . Since neutron emission is immediately preceded by beta emission, these lines terminate at elements of higher atomic number. The unsubstantiated possible decay by neutron emission of one Sb isotope ( $^{135}\text{Sb}$ ) is indicated by dotted lines and the symbol (-n?). Decay by alpha emission has not been indicated. The only fission-product mass chains which terminate in alpha-emitters are  $^{144}\text{Nd}$ , (half-life of  $10^{15}$  years) and  $^{147}\text{Sm}$ , (f.m., half-life of  $10^{11}$  years). The shielded nuclides  $^{152}\text{Eu}$  and  $^{146}\text{Pm}$ , which may be produced in very small quantities, decay partly to the alpha-emitters  $^{152}\text{Gd}$  ( $10^{14}$  years) and  $^{146}\text{Sm}$  ( $5 \times 10^7$  years), respectively. In some cases where isomerism occurs, it is not certain whether one of the isomers has a precursor or what its daughter nuclides are. In such cases dotted lines and question marks indicate the missing information.

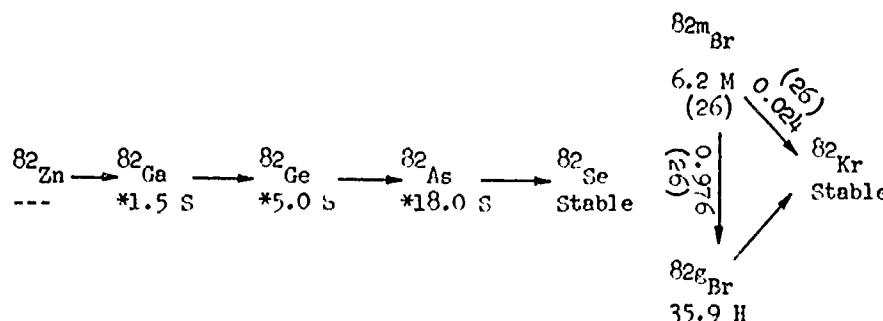
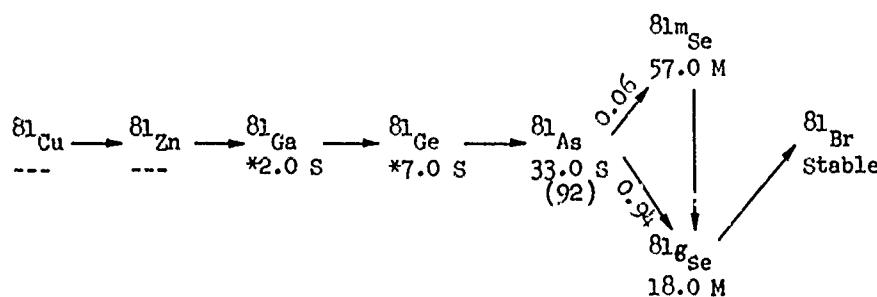
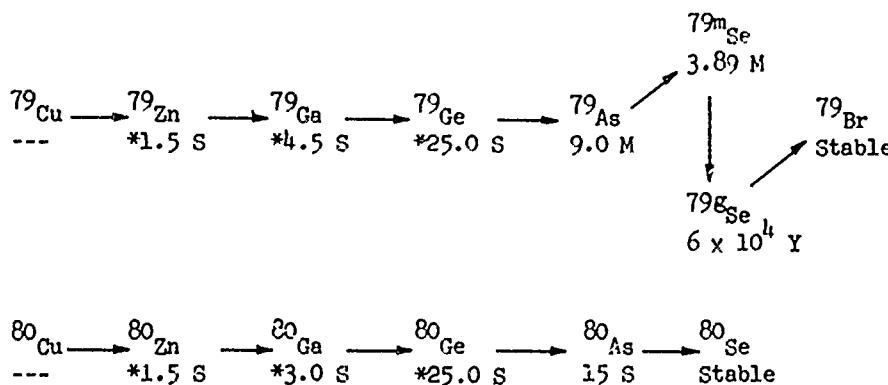
SCHEMATIC DIAGRAMS OF FISSION PRODUCT DECAY  
CHAINS: MASS NUMBERS 72 THROUGH 161

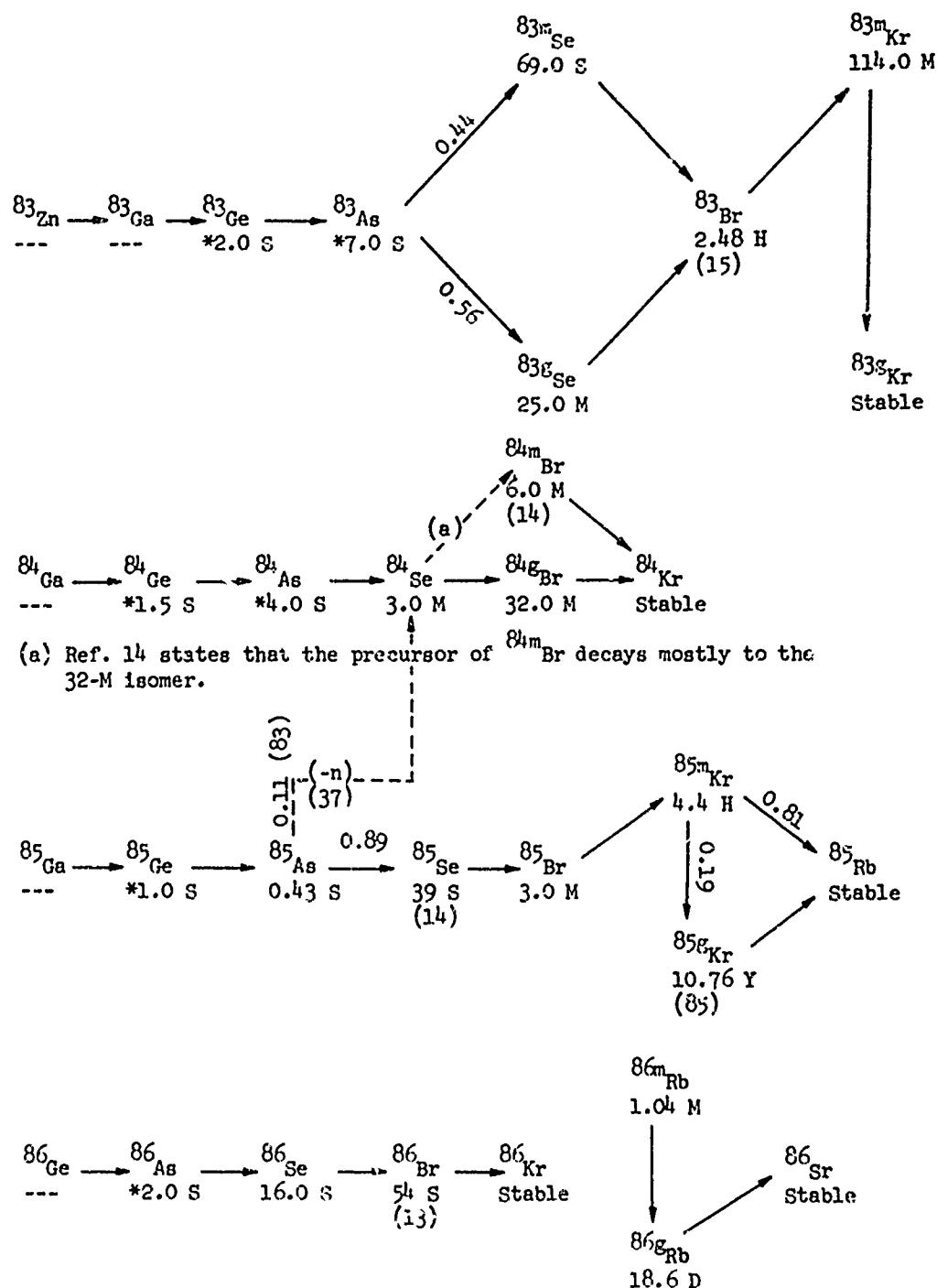


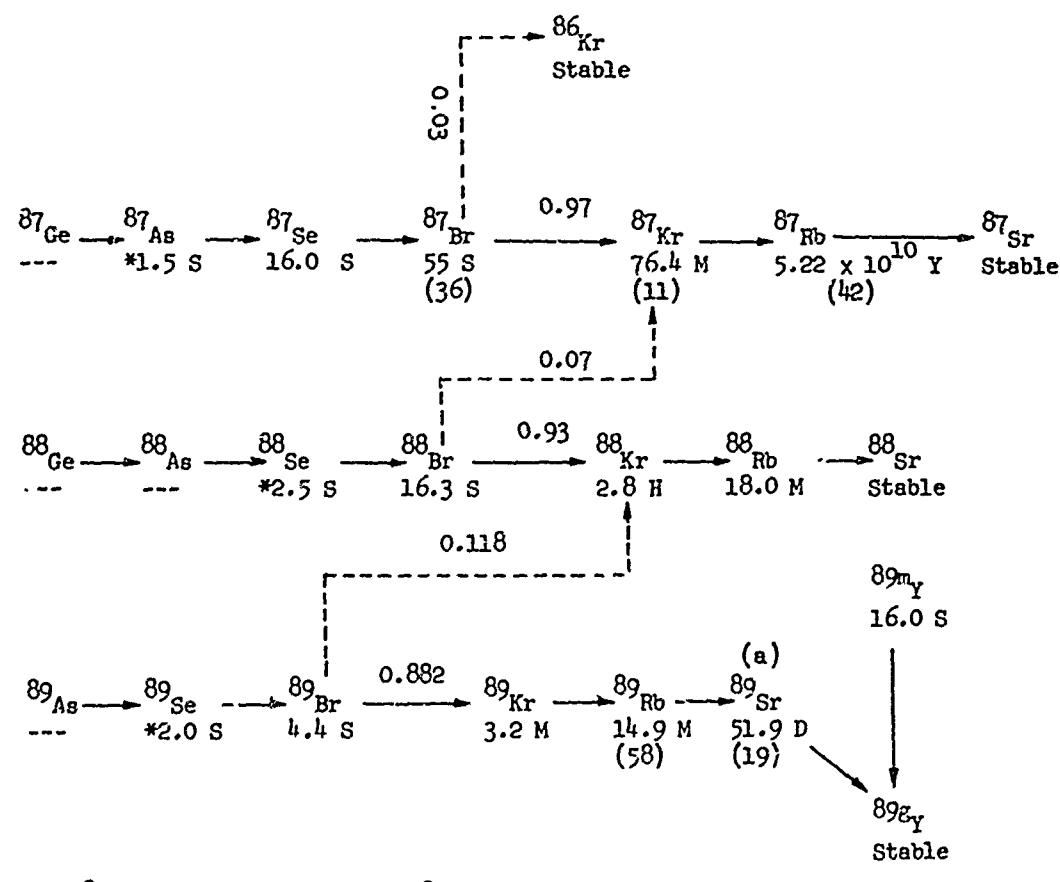
(a) Branching to  $^{77m}\text{Se}$  and its  $T_{1/2}$  taken from NDS.



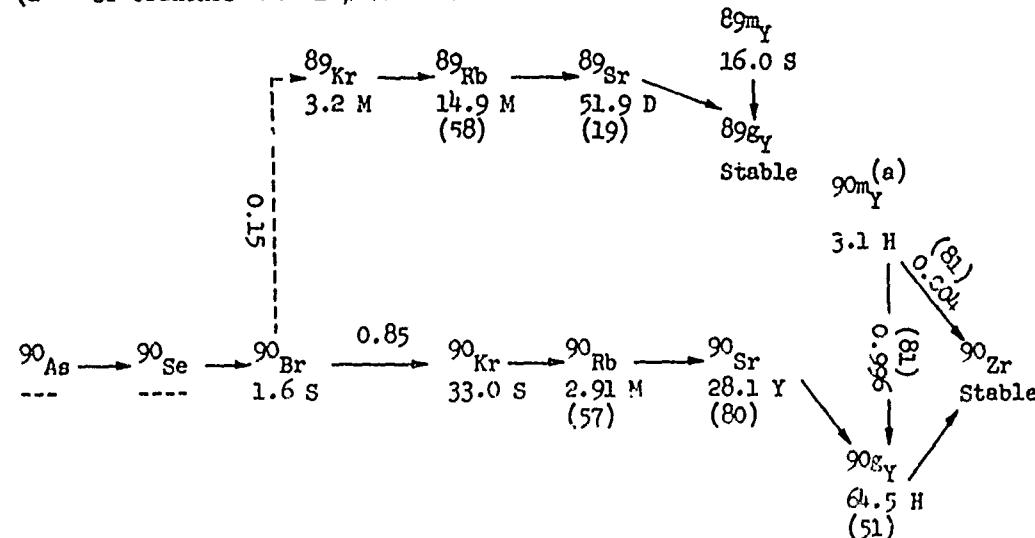
(a) Decay of  $^{78}\text{Ge}$  according to Ref. 84.



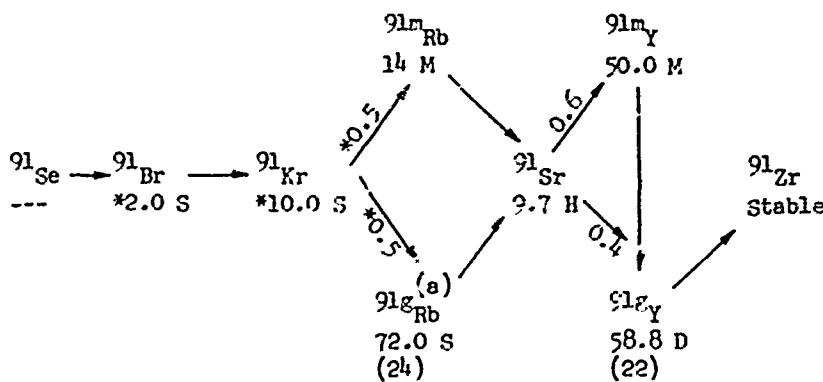




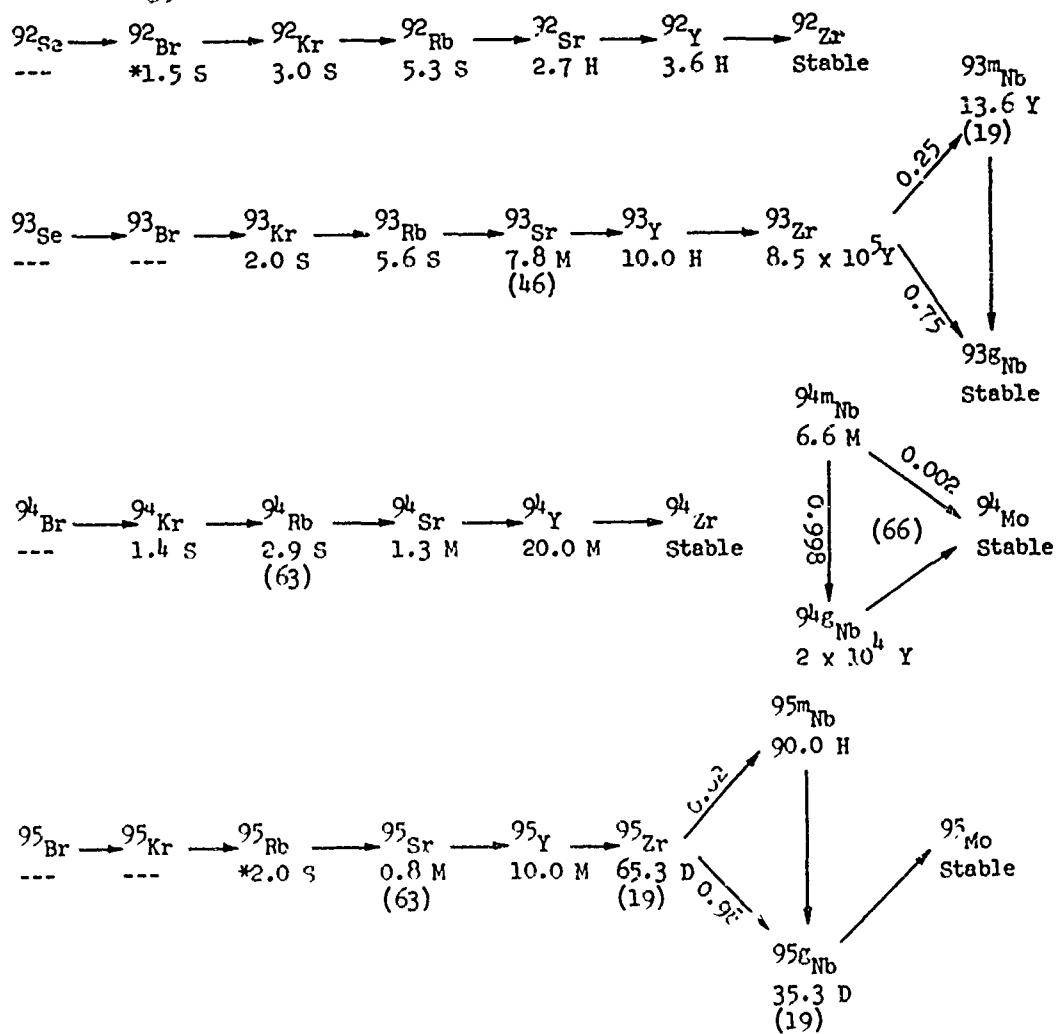
(a)  $^{89}\text{Sr}$  branches < 0.01 % to  $^{89}\text{m}_Y$ .

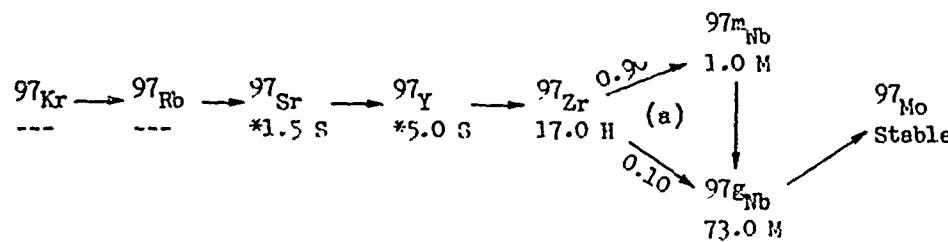
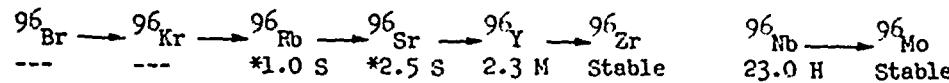


(a)  $^{90}\text{m}_Y$  is not the daughter of  $^{90}\text{Sr}$ , see Ref. 18.

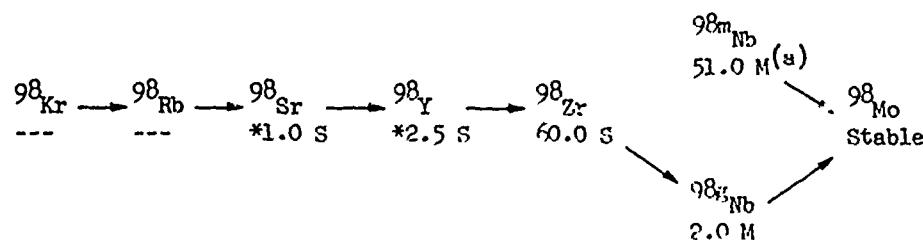


(a) Assignment of the short-lived isomer to the ground state follows an NDS suggestion.

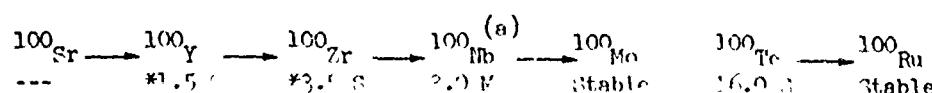
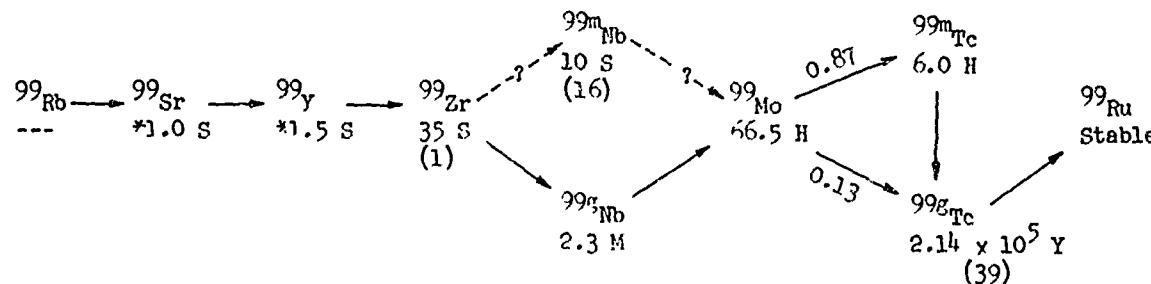




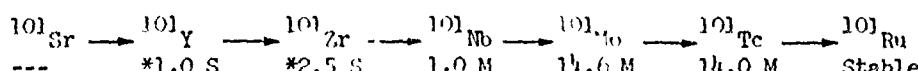
(a) Branching fractions, suggested by the NDS scheme, are approximate.

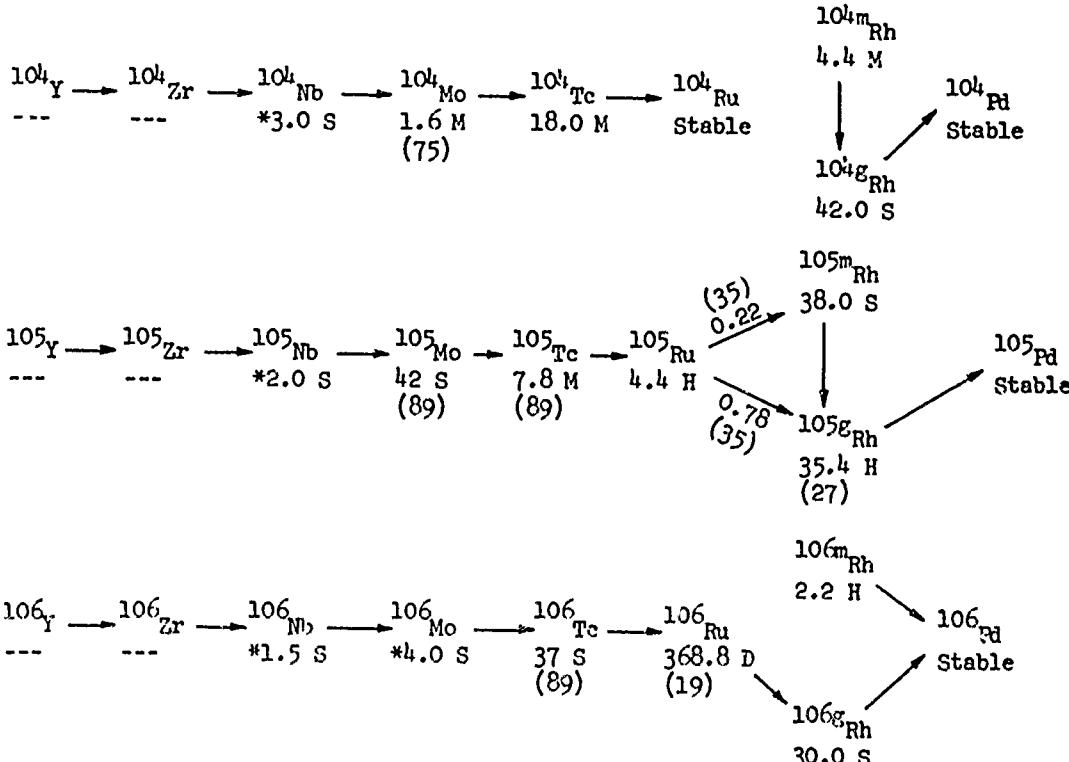
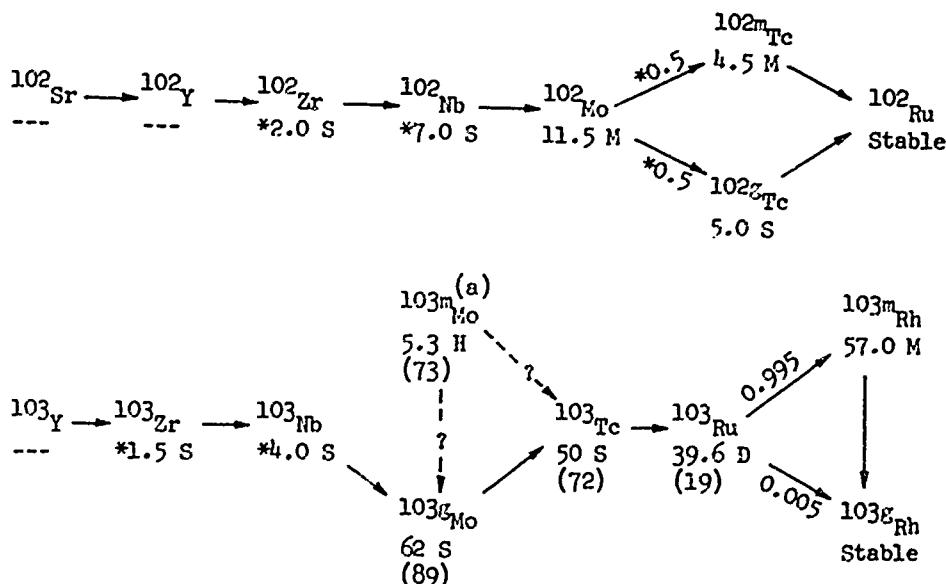


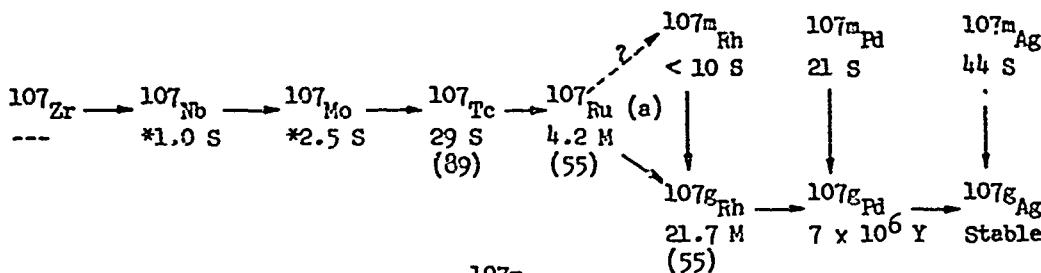
(a) The 51-M Nb has been observed, Refs. 1 and 17, but is not the daughter of  $^{98}\text{Zr}$ . The 2-M isomer is postulated in Ref. 1.



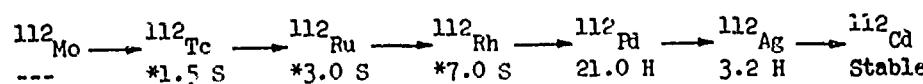
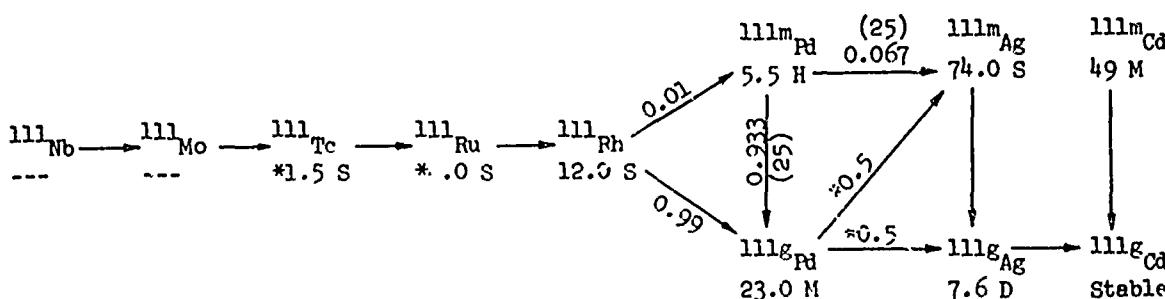
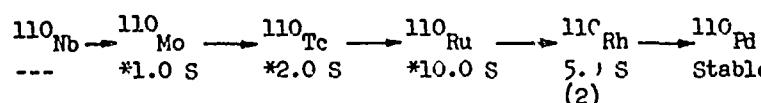
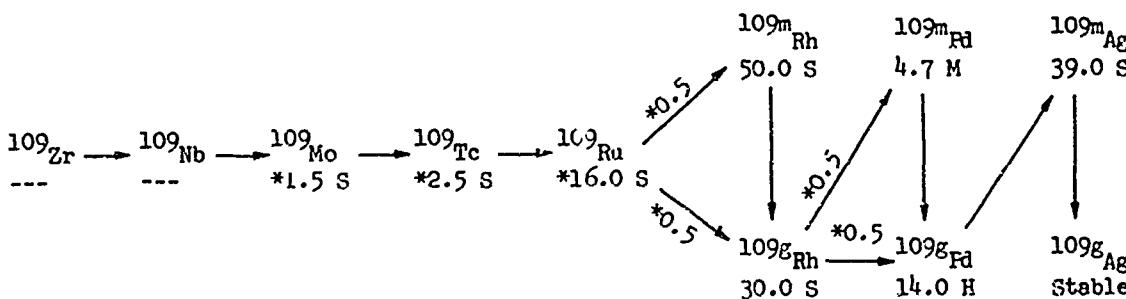
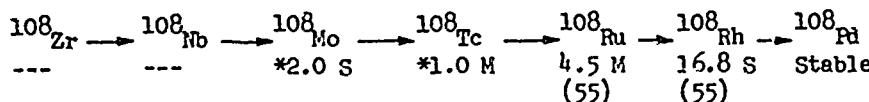
(a) NPS lists both a 5-M and a 11.5-M Nb state, but suspects they may be the same.

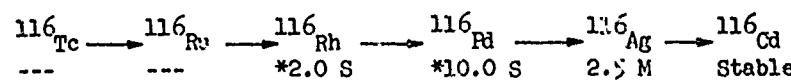
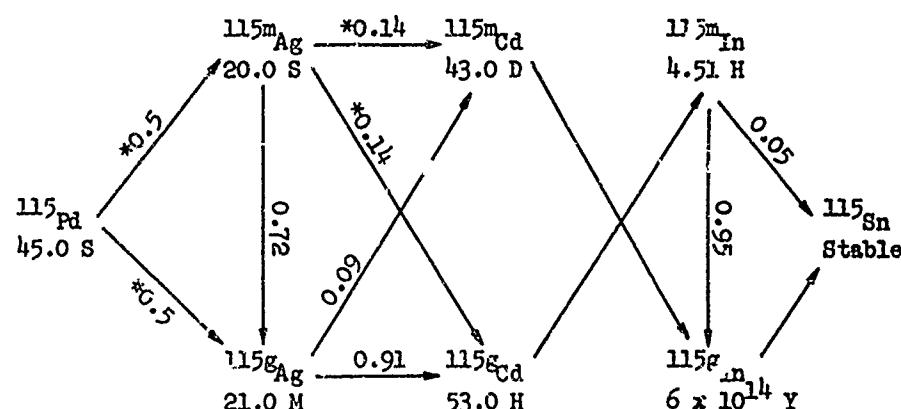
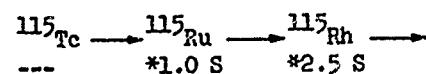
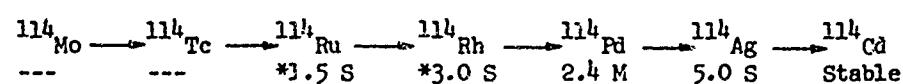
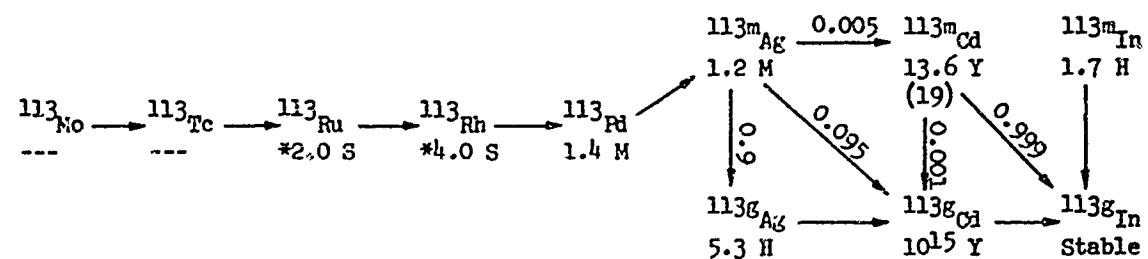


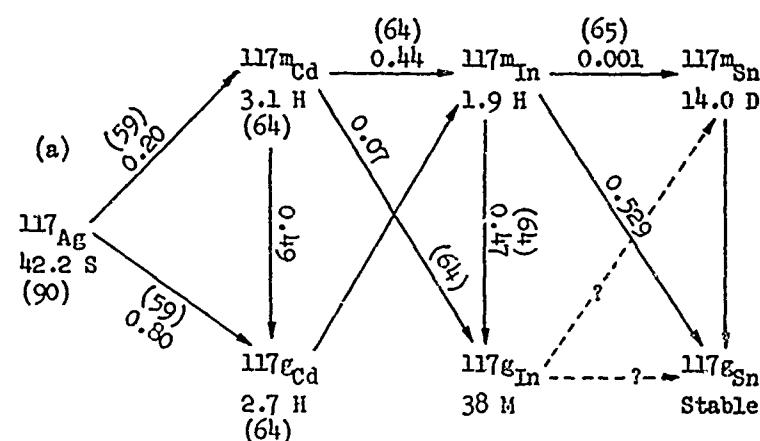
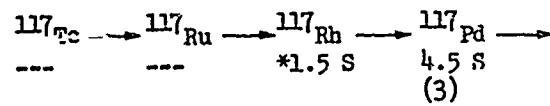




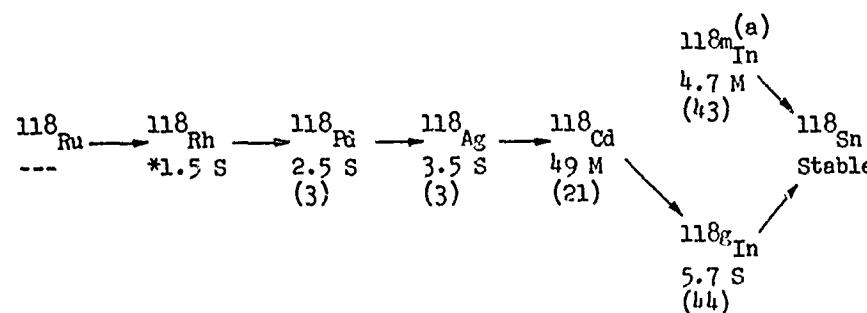
(a) Katcoff, Ref. D, showed a 45-S  $^{107}\text{m}$ Rh, referencing Coryell in a 1955 MIT report. However, NDS in 1960 stated that no short-lived isomer had been reported. In 1962 Pierson, Griffin and Coryell, Ref. 55, found only the 21.7-M state, but postulated that a < 10-S state, decaying by a strongly converted I.T. to the ground, existed. The 4.2-M Ru should decay mainly to one or the other of the Rh states but it could not be predicted which.



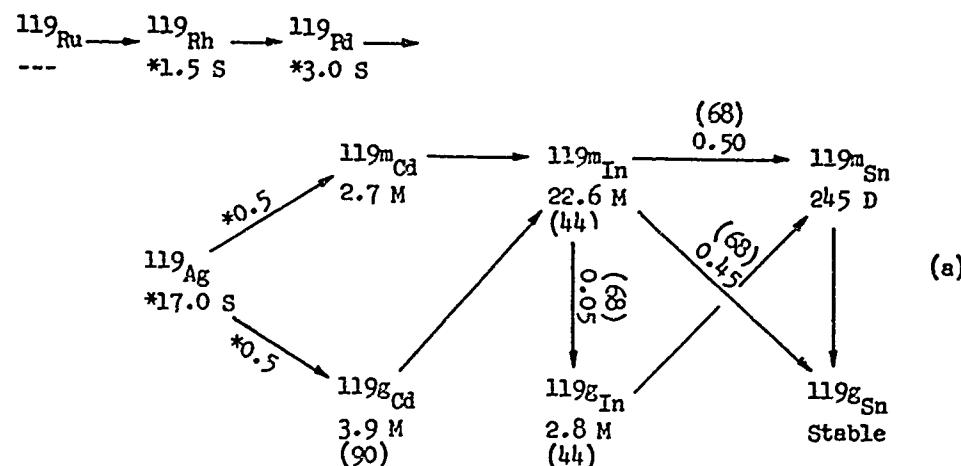




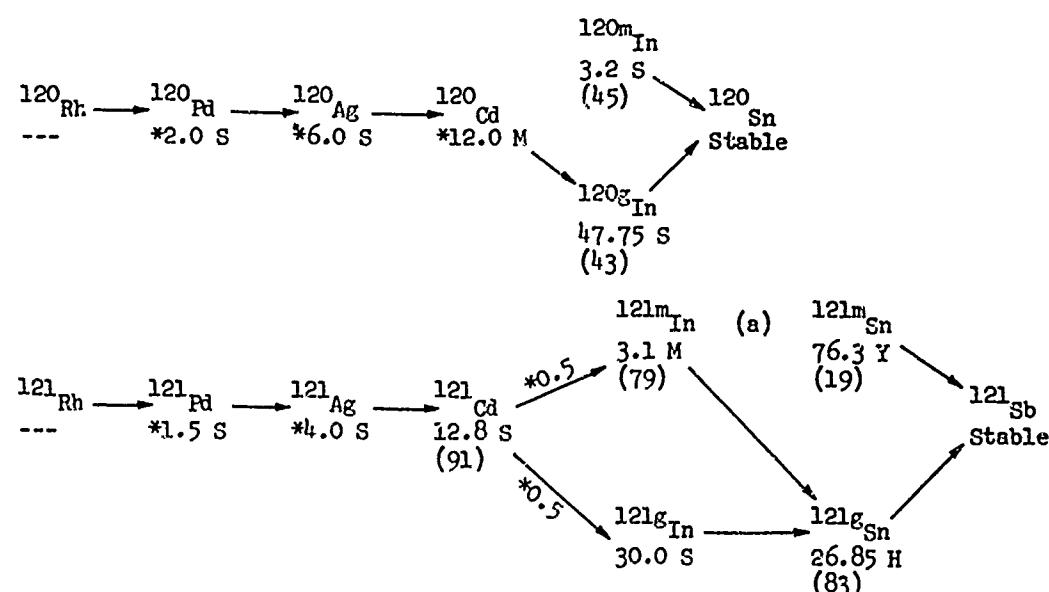
(a) Other versions, considerably different and equally plausible, could be constructed for the mass-117 chain branching from the available data; e.g. Refs. 33, 34, 59, 60, 64, and 65.



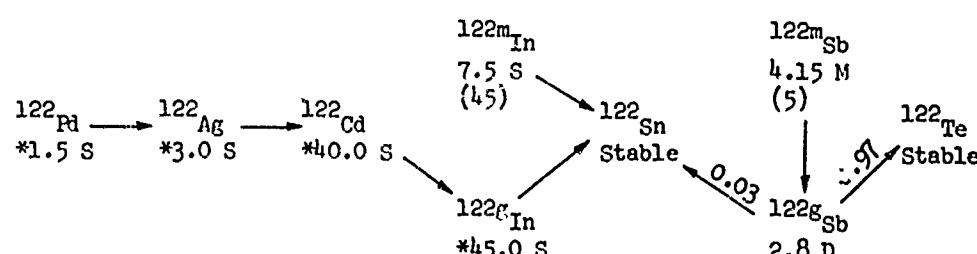
(a) Ref. 21 states that  $4.7 \cdot M^{118m}_{\text{In}}$  is not a daughter of  $^{118}_{\text{Cd}}$ .

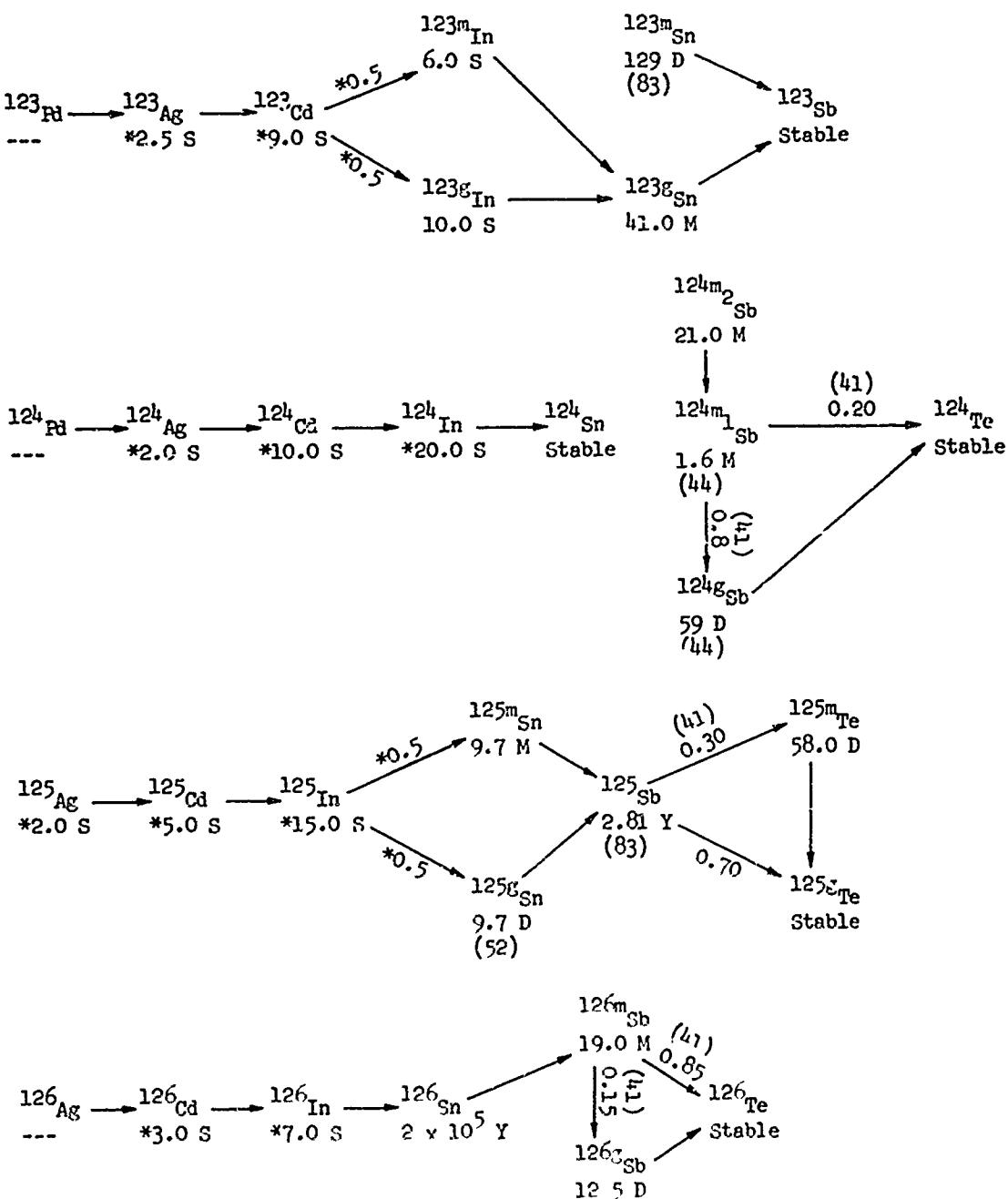


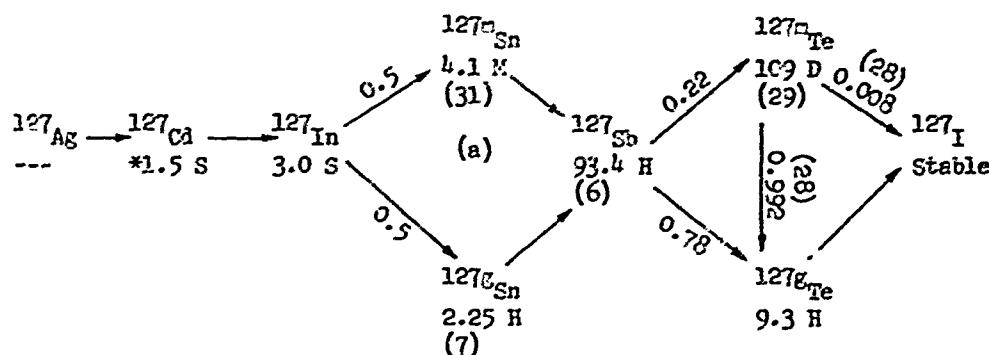
(a) Ref. 90 proposes a very different scheme for the Cd-In-Sn branching in this chain.



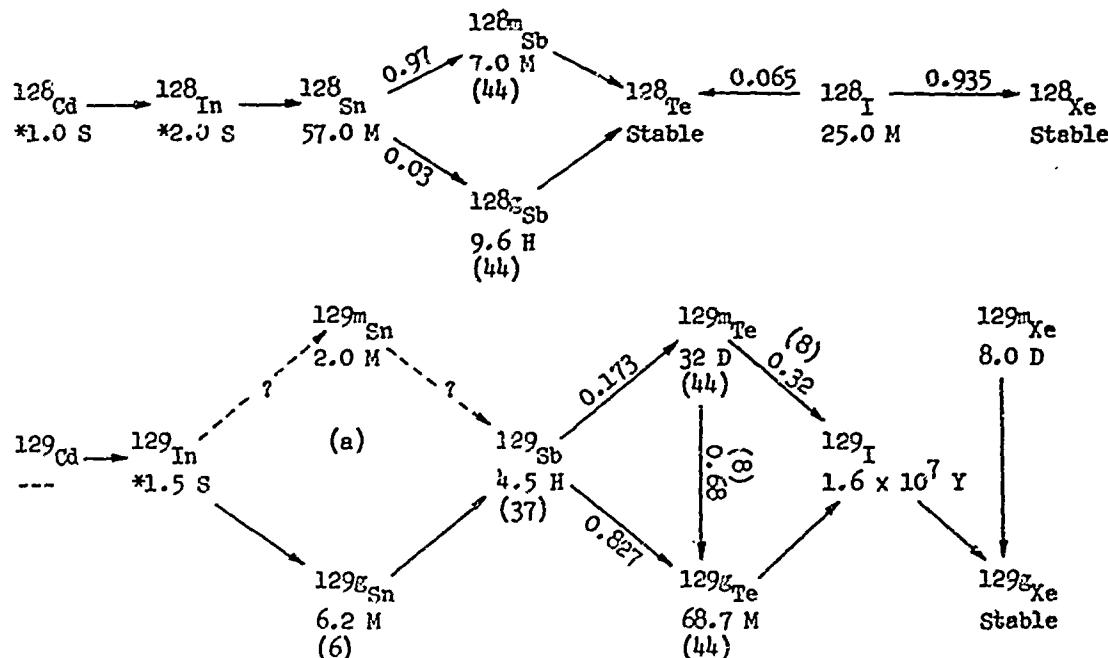
(a) In and Sn chain decay from Ref. 4



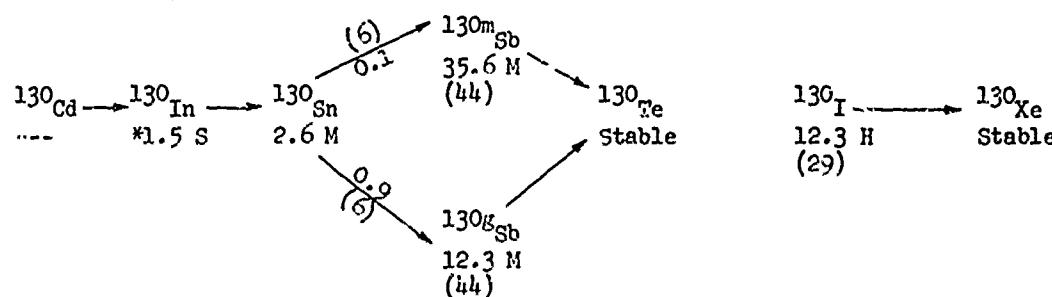


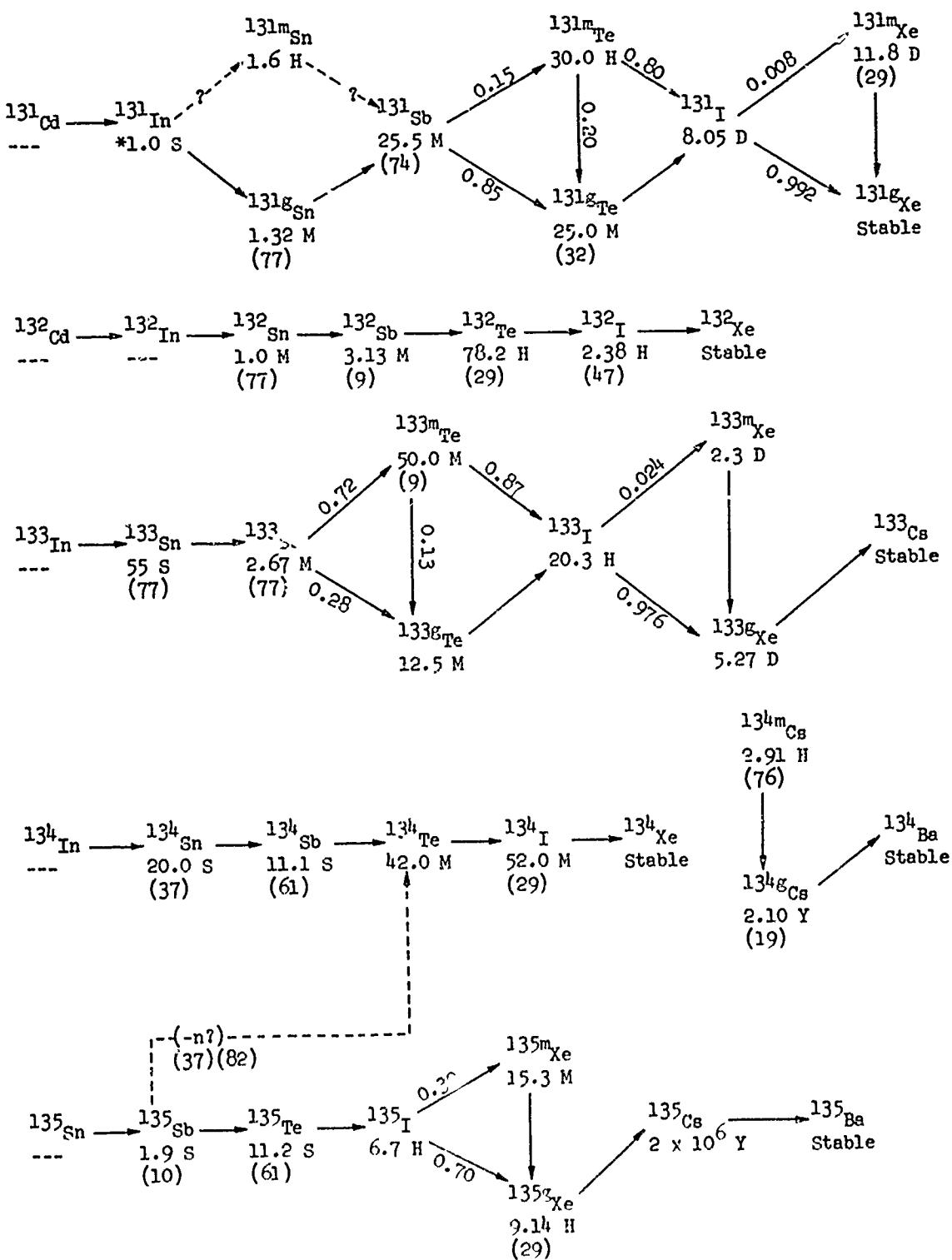


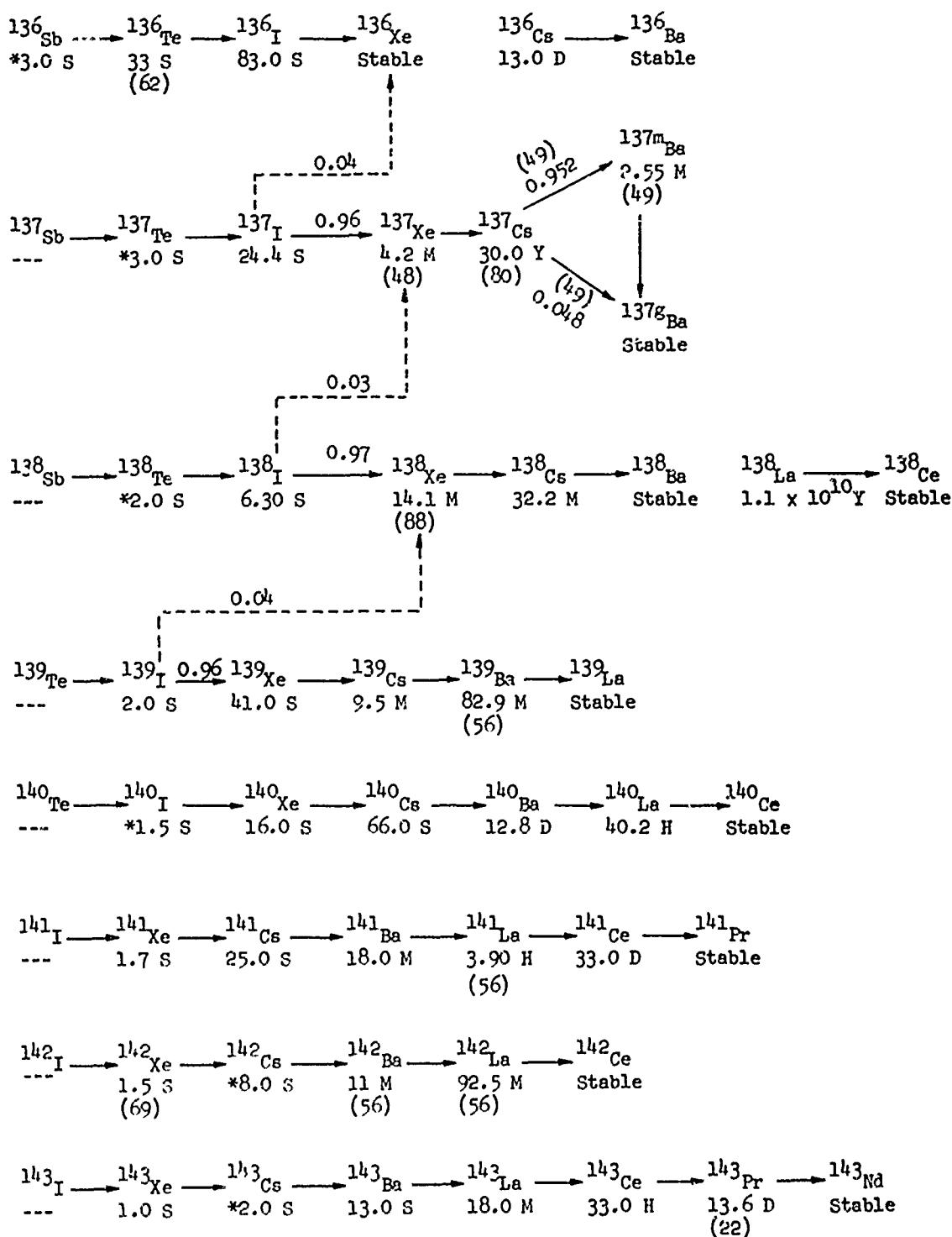
(a) The In and Sn portion of the chain decay is according to Ref. 7.

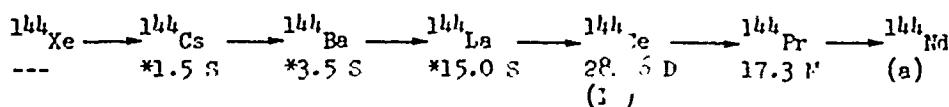


(a) The NDS 1961 sheet gives 1.8 H for  $T_{1/2}$  for  $^{129}\text{Sn}$ . Hagebø et al., J. Inorg. Nucl. Chem. 24, 1301 (1962) reported a 1.0 H and an 8.8 M state. Dropesky and Orth, Ref. 6 (1962), found only a 6.2-M state. Chu and Marinsky, Ref. 40 (1966), showed that Hagebø's 1.0-H isomer was an artifact and at the same time reported the 2-M isomer. It is not stated whether the 2-M or the 6.2-M isomer is the ground state. The assignment here is arbitrary.

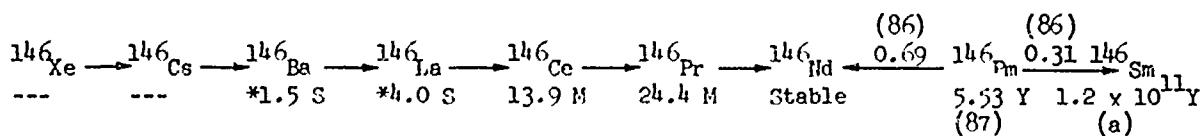
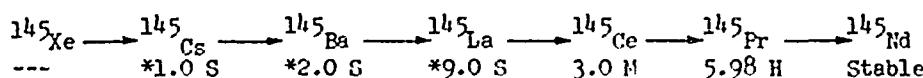




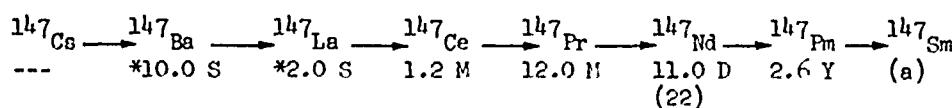




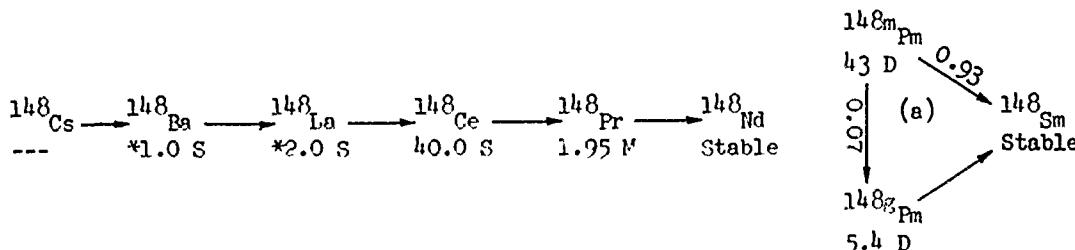
(a)  $^{144}\text{Nd}$  is an alpha-emitter with half-life of about  $2.4 \times 10^{15}$  Y, according to Ref. 50.



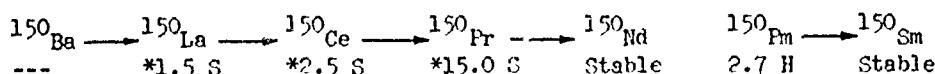
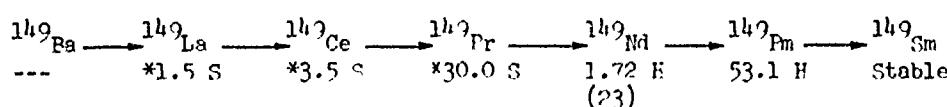
(a) The long-lived  $^{146}\text{Sm}$  decays by alpha emission to stable  $^{142}\text{Nd}$ .

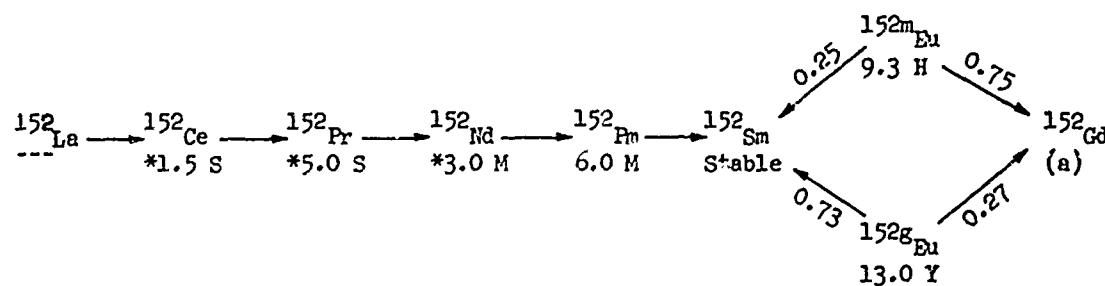
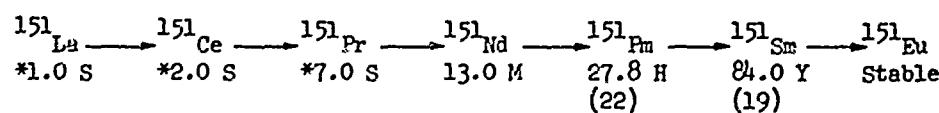


(a)  $^{147}\text{Sm}$  is an alpha-emitter with half-life of about  $10^{11}$  Y.

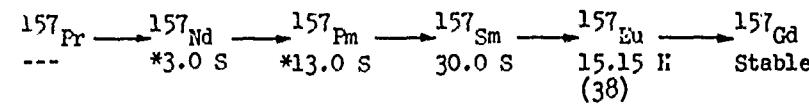
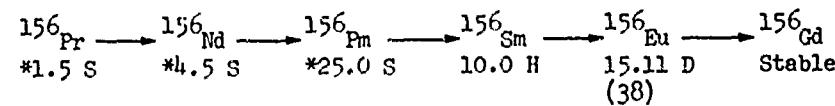
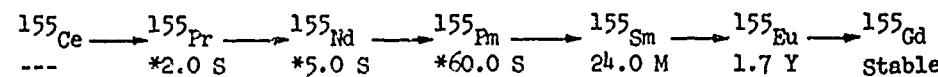
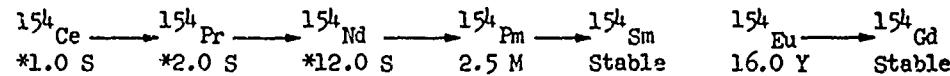
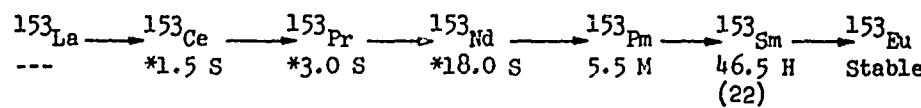


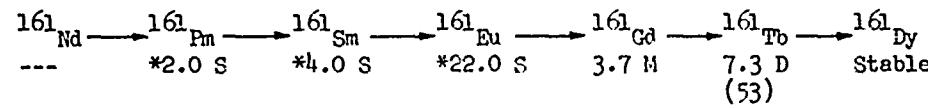
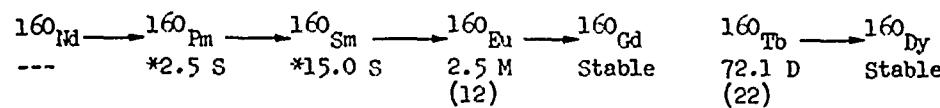
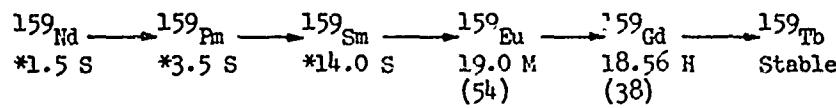
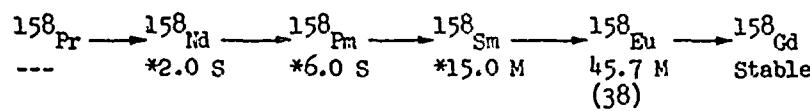
(a)  $^{148m}\text{Pm}$   $T_{1/2}$  and branching, from NDS.





(a)  $^{152}\text{Gd}$  is an alpha-emitter with half-life of about  $10^{14}$  Y.





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